25

Determining baseball bat performance using a conservation equations model with field test validation (Revised Aug 2000)

Lawrence P. Fallon, PE
Supervisor, Environmental and Special Test Facilities
C.S. Draper Laboratory, Inc., Cambridge, Massachusetts, USA

Robert D. Collier, Ph.D.
Adjunct Professor of Engineering, Dartmouth College
Hanover, New Hampshire, USA

James A. Sherwood, Ph.D., PE
Director, Baseball Research Center
University of Massachusetts, Lowell, Massachusetts, USA

Timothy Mustone
Graduate Research Assistant, Baseball Research Center
University of Massachusetts, Lowell, Massachusetts, USA

ABSTRACT: A series of laboratory tests were developed to determine the performance of baseball bats based on the laws of Conservation of Energy and Conservation of Momentum. In support of the conservation theory and laboratory tests, a field-test procedure was established to estimate the performance of bats based on a large statistical sample of real batted ball data.

With the help of Major League Baseball's (MlB) Twins, Royals and Devil Rays organizations, thousands of hits were recorded during field testing to provide validation of the laboratory tests and the Conservation Laws model. Significant differences between solid wood and high performance aluminum bats were documented. In addition, certain wood composite bats were also tested and found to have similar performance but were more durable than the traditional solid wood bats.

A variation of these test procedures has been adopted by MLB to approve wood-like composite bats for Class-A-Short-Season and Rookie-League play. The introduction of more durable wood-like bats offered significant savings to professional organizations while maintaining the integrity of the game. Following MLB's lead, collegiate and high school organizations are considering various test methods to help them control baseball bat performance. These organizations are driven not for economic reasons but for concerns such as player safety and a balance between offense and defense.

KEYWORDS

baseball bat, performance testing, conservation model

INTRODUCTION

Solid-wood baseball bats have been a part of MLB since its inception. In a sport where statistics are used to compare today's stars with the heroes of years past, it is important that the tools available to these players do not change. As the talent of the pitchers progressed through the years, hitters found themselves choosing lighter, relatively thin handled, ash bats to increase their swing speeds.

Because of the thin handles and the shortage of "good wood", bats became less durable and baseball more costly. In the 1960's, amateur baseball began using stronger aluminum bats for economic reasons. As technology and metal alloys advanced, these nonwood bats were designed with increased performance. Unlike their solid wood counterparts, hollow metal barrels undergo significant distortion during ball impact. A portion of the impact energy is stored in the deformed barrel and returned to the batted ball in a manner similar to that of a tennis racket or trampoline. Titanium superalloys were quickly made illegal by the governing bodies as fielders were at substantial increased risk of injury. However, aircraft quality aluminum in itself has increased the risk and resulted in higher-scoring, longer-duration games.

In addition to the increased batted ball speeds, the size of the sweetspot and hitting area on aluminum bats is significantly larger than that of wood. Players get singles and doubles with hits off aluminum handles where wooden bats would have splintered. The "safe-zone" over the inside corner of the plate is no longer there for pitchers.

With thousands of players in its minor leagues, MLB was faced with two concerns; the expense of replacing broken wooden bats and how to retrain a high school or college draft pick whose aluminum bat swing doesn't work with wood. Although it is unlikely that MLB will ever use anything but solid-wood bats in the majors, their minor league affiliates are in need of a durable wood-like bat. It is common for an organization to break dozens of bats in the batting cages during a single day of spring training.

Bat manufacturers are now developing wood bats that incorporate fiberglass and carbon composites into their designs to provide wood-like performance with substantially increased durability. Players that were discarding fractured bats after 100 hits can get over 1000 hits from one bat. MLB has used the principles of the research presented in this paper and begun approving wood-like composite bats for Class-A-Short-Season and Rookie-League play.

The authors of this paper began their research in baseball at Tufts University in Medford, Massachusetts in 1990. Early results were published by Collier in 1992. In 1996, this work was transitioned to the University of Massachusetts at Lowell. A series of laboratory tests were developed to determine the performance of baseball bats based on the laws of Conservation of Energy and Conservation of Momentum. In support of the conservation theory and laboratory tests, a field-test procedure was established to estimate the performance of bats based on a large statistical sample of real batted ball data. With the help of grants from MLB and Rawlings Inc., a Baseball

Research Center was established at UMass-Lowell in 1999. Improved techniques for profiling bat performance were developed with the acquisition of a hitting machine from Baum Research and Development Inc.

THE ENERGY EXCHANGE

During the collision of a bat and ball, energy is transformed from primarily kinetic to a multitude of forms. The pitcher conveys both linear and rotational kinetic energy on the ball. Typical kinetic energy values for a fastball reaching the plate at 90 mph and spinning at 1600 rpm are 85 ft-lb linear and 3 ft-lb rotational.

The energy imparted on a bat will vary significantly from hitter to hitter and swing to swing. During the swing, the pivot point for bat rotation is constantly changing as documented and modeled by Crisco. The goal of delivering maximum bat energy at contact results in linear and rotational kinetic energy of the bat as a rigid body. In addition, bat acceleration during swing will store potential energy in the curved bat handle. Ideally, the batter can control the bat's acceleration to allow the head of the bat to "whip" and maximize the transfer of this potential energy into "local" kinetic energy at the moment of impact.

A typical wood bat swung by a professional ballplayer may have a rigid body bat velocity of 75 mph, 6 in from the barrel end, and an angular speed of 350 rpm. The resulting rigid body kinetic energy of the bat (32 oz., 34 in., 11.5 in. CG, 2800 oz-in^2 Inertia$_{CG}$) is 242 ft-lbs. linear and 25 ft-lbs. angular assuming an instantaneous pivot point at the knob during impact.

High-speed video was used to study the potential energy stored in a bending bat during the swing. In addition, strain gages and accelerometers were used to monitor the handle strains and the timing of its release. Although the hitter's hands are not as rigid as a mechanical clamp, the deformed shape of a cantilever beam with an eight-inch handle clamp provided a good estimate for the potential energy stored and showed similar handle strains. The work required to deform the bat is equivalent to the stored potential energy.

For an end deflection of 1.5 inches, a clamped wood bat typically required a load of 37 lbs. at the six-inch point. Integrating the load and the deflection at the load point results in "whip" potential energy of only 2 ft-lbs. Mustone and Sherwood documented the minimal significance of the whip effect. Using a finite element model, ball exit velocities increased by less than 0.4 mph when a whip effect was applied.

During the collision, we can consider the bat to be unconstrained, the bat-ball contact time to be short relative to the speed at which the impulse travels towards the handle and the hitter cannot influence the ball outcome. The batted ball has linear and rotational kinetic energy as well as internal energy being dissipated as it oscillates through its flight. Likewise, the bat has some remaining linear and angular kinetic energy and potential energy resulting from the impulse that is dissipated through vibration and acoustic emission. Aluminum bats include a hoop mode that results in the "ping" as opposed to the "crack" of the wood bat. Both wood and metal bats have local energy loses associated with grain fracture in the wood and yielding of the metal.

In most cases, due to the ball's dynamic compression or its softness, only the first two or three bat beam modes are excited. Depending on the impact location, the first

two modes typically account for 90 to 99% of the bat vibration energy after impact. The high frequency hoop modes of aluminum bats, typically around 1000 Hz, have minimal energy. Van Zandt diagramed the elastic response of a bat after being struck by a ball.

Several dozen live-hitting bat-ball collisions were reviewed using high-speed video. Typical post-collision linear bat speeds were 50% of the pre-collision velocity. Angular velocities averaged one-third the pre-collision velocity and varied considerably due to impact location. A well-hit ball may leave the bat with a velocity of 105 mph and a 4000 rpm spin rate. Summaries of typical energy values associated with a collision are listed in Table 1 but do not include "whip" energy estimated at 2 ft-lb.

Table 1 Typical Pre- and Post-Collision Energy

	Linear	Angular
Bat Pre-Collision (ft-lb)	242	25
Ball Pre-Collision (ft-lb)	85	3
Bat Post-Collision (ft-lb)	115	6
Ball Post-Collision (ft-lb)	116	18
Losses (ft-lb)	100	

NOMENCLATURE

v_{1b} – ball velocity before impact
v_{1a} – ball velocity after impact
v_{2b} – bat velocity at cg before impact
v_{2a} – bat velocity at cg after impact
W_1 – ball weight
W_2 – bat weight
m_1 – ball mass
m_2 – bat mass
x_2 – bat length
x_i – impact location from barrel end
x_{cg} – cg location from barrel end
I_{2cg} – bat moment of inertia at cg
I_1 – ball moment of inertia about it's cg
ω_b – bat angular rotation before impact
ω_a – bat angular rotation after impact
g – gravity
U_{K1b} – ball kinetic energy before impact
U_{K2b} – bat kinetic energy before impact
U_{K1a} – ball kinetic energy after impact
U_{K2a} – bat kinetic energy after impact
U_{LL} – local bat and ball strain energy losses
U_{BM} – energy loses associated with bat beam modes
U_{MS} – miscellaneous losses not considered in the tests
C_e – COR adjustment to account for test conditions
C_H – hoop adjustment to account for test conditions
C_{MS} – miscellaneous loss constant

e_{LL} – local losses test coefficient of restitution
W_{M1} – work equivalent to energy stored in mode 1
W_{M2} – work equivalent to energy stored in mode 2
e – COR of the bat-ball collision
d_2 – batted ball distance

INTEGRATING THEORY AND LAB TESTS

Tests were developed to measure engineering properties of bats and balls so that the laws of conservation of energy and momentum could be used to predict bat performance. Tests focus on quantifying the energy losses associated with the collision. Factors were determined based on theory and computational analysis to compensate for test limitations. The energy losses considered by the lab tests include

1) internal frictional losses of the ball
2) internal frictional losses of the bat (local to the impact)
3) ball resonance (oscillations within the batted ball which get dissipated through damping)
4) local bat hoop modes
5) 1st two bending modes of the bat

These losses were determined by two series of tests. The first 4 losses are considered by measuring the COR of rigidly mounted bats with their bending modes eliminated. Compensations must be applied to make-up for test velocities, large deformation effects, double-sided barrel loading and wall resistance. The 5th loss is determined by performing a modal analysis, determining the impact location/modal influence coefficients and measuring the work required to deform the bat to these mode shapes. Again, test limitation factors must be applied.

Balls were projected off rigidly mounted bat barrels to measure the internal energy losses associated locally in the bat barrel and within the ball (U_{LL}). Input ball velocities were 60 mph. Input and rebound speeds were measured using an Oehler photocell system. A nonlinear factor (C_{LL}) is applied to compensate for ball nonlinearities due to lab-test and game-like collision energies. Additional collision energy effects are considered by the large deformation factor (C_H) due to hoop distortion in barrels. The hoop stiffness decreases approximately 13% under game-like collision conditions resulting in an 8% increase of the energy-storing capability in the bat.

The energy loss associated with bat beam modes (U_{BM}) is determined by a series of tests. First, a modal analysis is performed to determine the bat's first two bending mode frequencies and the location of the associated nodal points. A hoop mode is also noted for barrels of shell construction. Next, influence coefficients are determined by measuring the transfer functions along the length of the bat during barrel impacts. The impacts are applied through a baseball on an impact hammer. The impacts are applied along the barrel in the normal hitting area.

Due to the ball's dynamic compression, a negligible amount of energy is transmitted into the bat's third bending mode. Static three- and four-point bending tests are performed with the bats supported at the first and second mode nodal points.

Loads are applied at a point, or points, to create a deformed bat shape that is similar to the mode shape.

The underlying theory is that following the bat-ball collision, the majority of the potential and kinetic energy (excluding rigid body motion) stored in the bat will be dissipated through the primary and secondary bending modes. The energy for each mode is purely potential when mode shape deformation is greatest and this energy is equivalent to the work required to statically deform the bat to that shape. Losses not associated with local bat-ball deformations can be computed by estimating the collision energy and using this approach with adjustments for higher order modes, hoop, acoustic and damping losses. The conservation of energy is

$$U_{K1b} + U_{K2b} = U_{K1a} + U_{K2a} + U_{LL} + U_{BM} + U_{MS} \tag{1}$$

where:

$$U_{K1b} = \frac{1}{2} m_1 v_{1b}^{\ 2} + \frac{1}{2} I_1 \omega_{1b}^{\ 2} \tag{2}$$

$$U_{K2b} = \frac{1}{2} m_2 v_{2b}^{\ 2} + \frac{1}{2} I_{2cg} \omega_{2b}^{\ 2} \tag{3}$$

$$U_{K1a} = \frac{1}{2} m_1 v_{1a}^{\ 2} + \frac{1}{2} I_1 \omega_{1a}^{\ 2} \tag{4}$$

$$U_{K2a} = \frac{1}{2} m_2 v_{2a}^{\ 2} + \frac{1}{2} I_{2cg} \omega_{2a}^{\ 2} \tag{5}$$

$$U_{LL} = \frac{(U_{K1b} + U_{K2b})[(C_{LL} e_{LL} - 1) v_T]^2 m_1 C_H}{2U_T} \tag{6}$$

$$U_{BM} = C_{BM}\left(\int F_{S1} dx_{S1} + \int F_{S2} dx_{S2}\right) \tag{7}$$

$$U_{MS} = C_{MS}(U_{K1b} + U_{K2b}) \tag{8}$$

LABORATORY TESTS

Three models of bats were used in the laboratory testing. A series of baseline tests were performed and the resulting average properties are listed in Table 2. Also included in Table 2 is a projected swing speed (6 in from the barrel's end) related to the bat's inertia. Examining player's swings with a variety of weighted bats using high-speed video developed this relationship.

Table 2 Baseline Property Data

	Wood	Aluminum	Composite
Length (in)	34.0	34.0	34.0
Weight (oz)	31.9	30.1	31.8
CG (in)	11.0	12.8	11.4
I_{CG} (oz-in^2)	2740	2780	2750
Swing (mph)	69.7	73.6	70.4
Swing Energy Linear (ft-lb)	228.2	213.5	225.1
Swing Energy Ang. (ft-lb)	28.5	33.0	29.1

Barrel testing was performed using MLB approved baseballs. Velocities were measured as balls were projected off rigidly mounted barrels at input speeds of 60 mph (V_T). Impacts were performed at 2, 6 and 10 inches from the end of the barrels. The resulting test input energy (U_T) is 39 ft-lbs. By comparing the test conditions (input velocity, double sided barrel loading and wall resistance) to typical game-like conditions, an adjustment can be made to compensate for ball COR nonlinearities. COR data measured at UMass-Lowell estimated that C_{LL} should be set to 0.85.

Today's high-performance aluminum alloy bats consist of thin walls that respond nonlinearly due to large deformations as the barrels distort. Comparing game-like and laboratory test condition, results in a 13% decrease in bat hoop stiffness during game-like conditions. This decreased stiffness translates to an 8% increase in the percentage of energy stored in the barrel during impact. Adair notes that the barrel distortion of an aluminum bat during impact is one-tenth the distortion of the ball. The result is a C_H of 0.9928 for metal bats of shell construction and a C_H of 1.0 for bats of solid construction. Table 3 contains the results of the barrel testing.

Table 3 Barrel Test Results

	Wood	Aluminum	Composite
2 in Impact e_{LL}	0.581	0.621	0.590
2 in Impact U_{LL} (ft-lb)	92.9	80.0	89.6
6 in Impact e_{LL}	0.582	0.625	0.591
6 in Impact U_{LL} (ft-lb)	92.6	77.6	89.3
10 in Impact e_{LL}	0.578	0.618	0.586
10 in Impact U_{LL} (ft-lb)	93.7	80.5	90.8

Note: Distances given from barrel end of bat.

Modal analysis was used to determine the nodal points and natural frequencies of one bat of each modal. The bats were freely suspended during testing. Influence coefficients were determined by applying an impact load along the barrel and measuring the dynamic response at other locations. The transmissibilities were normalized and a scaling factor was applied to the resulting displacements to match those measured on wood bats in the field. For the first mode, the displacements were tabulated at 17 in from the barrel end as this is the approximate location of maximum displacement for the first resonance of each bat. Similarly, second mode displacements were profiled at 26 in from the barrel end. The results of the modal testing are summarized in Table 4.

Table 4 Modal Test Results

	Wood	Aluminum	Comp.
1st Freq. (Hz)	143	174	160
2nd Freq. (Hz)	481	627	523
3rd Freq. (Hz)	968	1314	1025
1st Mode Barrel Node Loc. (in)	7.1	6.4	6.8
2 in Impact C_I's	0.41 / 0.10	0.22 / 0.05	0.40 / 0.08
5 in Impact C_I's	0.21 / 0.02	0.11 / 0.00	0.21 / 0.02
8 in Impact C_I's	0.08 / 0.06	0.07 / 0.03	0.06 / 0.08
11 in Impact C_I's	0.37 / 0.12	0.20 / 0.09	0.30 / 0.08
14 in Impact C_I's	0.66 / 0.18	0.37 / 0.11	0.55 / 0.14
17 in Impact C_I's	1.00 /0.08	0.47 / 0.03	0.85 / 0.05

Notes: 1. Distances given from barrel end of bat.
2. C_I's = Influence coefficients for the first and second modes respectively. Values represent the normalized displacement at 17 in and 26 in associated with each mode.

Static stiffness profiling was performed on each bat model using a three-point bending test. Supports were positioned at the nodal locations identified by the modal analysis. A 500 lb load was incrementally applied 17 inches from the barrel end and displacements were monitored along the length of the bat at 3-inch increments. Next, a scaling factor was applied to compensate for the differences between the static laboratory load and the dynamic impact load of the bat-ball collision. This factor, C_{BM}, was estimated to be 3.0 by comparing static deflections on wood bats with the recoil observed during field play using accelerometers and high-speed video. By projecting the bat's maximum modal deformation prior to damping resulting from the bat-ball collision, the energy loss associated with this mode can be estimated by the work required to deform it statically.

By repeating this procedure using a four-point setup, the losses associated with the second resonance can be estimated. However, for this study finite element models of the bats were generated and the deflections were determined by numerical methods. In order to obtain a better match between the static deformation and the mode shape, a small second load was also applied. The results of the static testing are summarized in Table 5.

Table 5 Static Test Results

	Wood	Aluminum	Composite
17 in load δ_{17} (in)	0.33	0.16	0.28
2 in Load W_{M1} (ft-lb)	25.8	13.7	25.3
5 in Load W_{M1} (ft-lb)	12.9	6.6	13.3
8 in Load W_{M1} (ft-lb)	5.3	4.3	3.9
11 in Load W_{M1} (ft-lb)	23.4	12.6	18.6
14 in Load W_{M1} (ft-lb)	41.5	23.3	34.7
17 in Load W_{M1} (ft-lb)	62.2	29.6	53.3
2 in Load W_{M2} (ft-lb)	4.3	2.0	3.4
5 in Load W_{M2} (ft-lb)	0.9	0.0	0.8
8 in Load W_{M2} (ft-lb)	2.9	1.3	3.4
11 in Load W_{M2} (ft-lb)	5.1	3.8	3.4
14 in Load W_{M2} (ft-lb)	8.0	4.6	5.9
17 in Load W_{M2} (ft-lb)	3.6	1.3	2.1

Notes: 1. Response deflection (δ_{17}) is located at 17 in from the barrel end When subjected to a 500 lb load.
2. Work results incorporate the factored modal displacements for the applied impact location and the scaling factor, C_{BM}.

PERFORMANCE PREDICTIONS

Performance predictions can be made along the profile of the bat by substituting the test results into the equations. Some interpolation is required to correlate the individual test results, as the data test points were not always identical at each step. The conservation of energy equation, (1), has 2 unknowns when the laboratory testing is complete. By utilizing the law of conservation of momentum we can solve for the exit velocities. The simplest way to accomplish this is to solve for the overall bat-ball COR using the test data and energy equation.

$$e = \left[\frac{U_{K1b} + U_{K2b} - U_{LL} - U_{BM} - U_{MS}}{U_{K1b} + U_{K2b}} \right]^{0.5} \tag{9}$$

By substituting the definition of COR into the conservation of momentum equations, Watts and Bahill were able to calculate the batted ball velocity using equation (10).

$$v_{1a} = \frac{\left[v_{1b}\left(e - \frac{W_1}{W_2} - \frac{W_1 (x_{cg} - x_i)^2}{I_{2cg}} \right) + (1+e)\left(v_{2b} + (x_{cg} - x_i)\omega_{2b}\right) \right]}{\left(1 + \frac{W_1}{W_2} + \frac{W_1 (x_{cg} - x_i)^2}{I_{2cg}} \right)} \tag{10}$$

Based on the batted ball exit velocity, Adair projected typical batted ball distances. Table 6 summarizes the laboratory test results with a 3-point performance profile across the barrels of a wood, an aluminum and a composite baseball bat.

Table 6 Lab Test Performance Summary

	Wood	Aluminum	Composite
e at 2 in	0.424	0.526	0.438
v_{la} at 2 in (mph)	93.2	100.9	94.0
d_{la} at 2 in (ft)	318.9	356.3	322.8
e at 6 in	0.496	0.573	0.507
v_{la} at 6 in (mph)	108.1	115.1	109.1
d_{la} at 6 in (ft)	393.1	430.3	398.1
e at 10 in	0.453	.536	0.479
v_{la} at 10 in (mph)	98.5	110.0	102.4
d_{la} at 10 in (in)	344.8	403.0	364.2

FIELD TESTS

Field-testing was completed by measuring the batted ball distances from thousands of hits under controlled conditions. Field-testing is important for obtaining "game-like" results that complement the controlled laboratory measurement. Over 1000 hits per bat model were recorded using over 80 professional ballplayers from the Twins, Royals and Devil Rays minor league organizations (Rookie League through Class AA). Batted-ball distances are compared to those of the solid-wood bats across several different categories. Every effort was made to negate the variable effects such as environment, player caliber and player fatigue.

The ball field was staked out so that batted ball distances greater than 250 feet could be measured to an accuracy of ±5 feet, including balls hit over the fence up to 450 ft. Pitch speed was approximately 65-70 mph using both a pitching machine and live pitching. Player and bat rotation were used to eliminate the effects of player fatigue, player warm-up and environmental conditions. All contacts were recorded as a hit and measurements were recorded to the spot in which the ball first contacted the ground. The results of the field tests are summarized in Table 7.

Table 7 Field Test Statistical Summary

	Wood	Aluminum	Composite
Longest Hit (ft)	390 - 400	430 - 440	400 - 410
% Hits over 250 ft	33.5	37.3	33.7
% Hits over 300 ft	12.8	21.8	12.7
% Hits over 350 ft	3.0	8.3	2.7
Avg. Distance for Hits over 250 ft (ft)	294.4	315.4	295.4
Avg. Distance for Hits over 300 ft (ft)	332.3	347.6	333.8
Avg. Distance for Hits over 350 ft (ft)	368.7	386.3	368.0

The results of the field-testing clearly show the performance differences between the aluminum and wood bats. In fact, with fences averaging a little over 350 feet, you would expect 2.5 to 3 times as many homeruns if aluminum bats were used in MLB. The composite bat had similar results as the wood bats although some composite models observed no fractures compared to their wood counterparts that broke on average every 150-200 hits.

RESULTS

The field data provided a realty check of the laboratory test results. Although there are currently some accuracy limitations to the test procedures and theory, the basic principle of applying the conservation equations technique for determining bat performance was validated. A comparison of the field and laboratory results is provided in Table 8.

Table 8 Lab and Field Test Comparison

	Wood	Aluminum	Composite
LAB TESTS			
Weight (oz)	30.1-34.4	30.1	31.8
Cg Location (in)	10.7-12.0	12.8	11.4
Stiffness [1]	90-110%	145%	120%
Static Strength [1]	94-106%	172%	133%
1st Res. Freq. (Hz)	125-165	174	160
1st Barrel Node (in)	6.7-7.3	6.4	6.8
Barrel Elasticity [1]	99-101%	107%	101%
Est. Hit Dist. (ft)	388-398	430	398
FIELD TESTS			
Avg. Hit Dist. (ft) [2]	0.0	+21.0	+1.0
Max. Hit Dist. (ft) [3]	400	440	410

Notes: 1. Relative to average solid wood bat.
2. Fly balls over 250 feet relative to solid wood.
3. Measured to the nearest 10 feet.

A performance profile along the barrels of the bat using the laboratory results is presented in Figure 1. As the impact location moves away from the end of the barrel, the ball exit velocity off the aluminum bat does not drop off as fast as the ball exit velocity off of the wood and composite bats resulting in a larger sweetspot. With the stiffness of the composite bat slightly greater than that of the wood bat, it too has a slightly larger sweetspot. What is not indicated is the effective hitting area. As the impact location moves towards the handle, the wood bat will result in a fracture resulting in even a further reduction in performance.

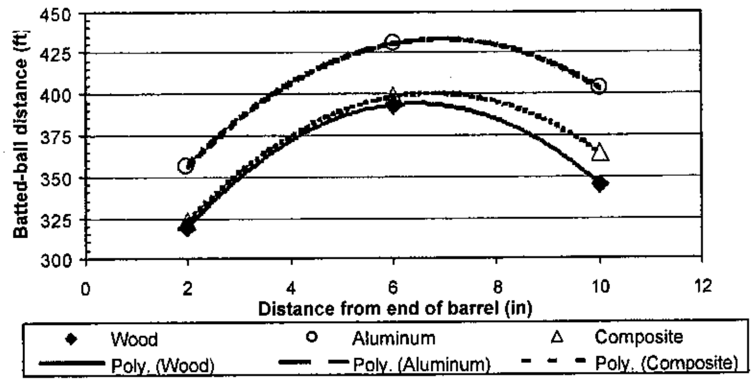

Figure 1 Performance Profiles

CONCLUSIONS

A laboratory test procedure was developed to determine the performance profile along the barrel of baseball bats. The theory behind the test was based on the laws of Conservation of Energy and Conservation of Momentum. Three bats of different material and construction were evaluated using these procedures. The method clearly demonstrated the superior performance of the aluminum bats over the wood and composite bats.

In support of the theory, a comprehensive field test program was used to compile batted ball distances with the different bat models. The performance differences measured between aluminum and wood bats in the laboratory were complimented by the field test results.

REFERENCES

Adair, R. (1994) *The Physics of Baseball*, Harper and Row

Collier, R. (1992) *Material and Structural Dynamic Properties of Wood and Wood Composite Professional Baseball Bats*, Proceedings of the Second International Congress on Recent Developments in Sound and Vibration

Crisco, J.J. (1997) *NCAA Research Program on Bat and Ball Performance*

Mustone, T. and Sherwood, J. (1998) *Using LS-DYNA to Characterize the Performance of Baseball Bats*

Van Zandt, L. (1992) *The Dynamic Theory of the Baseball Bat*

Watts, R. and Bahill, T. (1990) *Keep Your Eye on the Ball*, W. H. Freeman and Company